

# YAMATO-791197: A VOLATILE TRACE ELEMENT RICH LUNAR HIGHLANDS SAMPLE FROM ANTARCTICA\*

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**Abstract:** Neutron activation analysis of Ag, Au, Bi, Cd, Co, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U and Zn in Yamato-791197 reveals that many elements are enriched and heterogeneously distributed compared with Allan Hills A81005. While both samples derive from the lunar highlands, perhaps the same region, they were never part of the same rock. Trace element contents in Y-791197 resemble those in Apollo 66095 ("Rusty Rock"), a unique sample rich in condensed lunar volcanic exhalation.

## 1. Introduction

From the first discoveries of Antarctic meteorites, the presence of a substantial complement of meteorites of rare or unique type compared with the non-Antarctic one was recognized (KUSUNOKI, 1975). To date, over 7000 fragments have been recovered, mainly during the past decade by Japanese and U.S. teams (YANAI and KOJIMA, 1985a; ANTARCTIC METEORITE WORKING GROUP, 1985): unusual meteorites surface regularly. In January 1982, a 31.4 g sample, Allan Hills (ALH) A81005, was recovered and recognized as of possible lunar origin (MARVIN, 1983). A 22-group Consortium, created to study this, unanimously concluded that ALHA81005 derived from a portion of the lunar highlands not previously sampled by the Apollo or Luna programs (e.g. MARVIN, 1983; VERKOUTEREN *et al.*, 1983).

As part of this Consortium, VERKOUTEREN *et al.* (1983) used radiochemical neutron activation analysis and atomic absorption spectrophotometry to determine siderophilic As, Au, Co, Ga and Sb, lithophilic Cs, Rb and U and volatile/mobile Ag, Bi, Cd, In, Se, Te, Tl and Zn in duplicate 70-mg chips. Contents of 5 elements (Co, Ga and the lithophiles) reflected only lunar highlands crustal processes: the other 11 elements indicated micrometeorite admixture ( $1.3 \pm 0.5\%$  Cl equivalent) or slight redistribution by thermal processes on the lunar surface. For example, Cd—the most mobile element determined by VERKOUTEREN *et al.* (1983)—is enriched somewhat above the 1.3% Cl-equivalent level in ALHA81005: Cd, Pb and Zn had previously shown similar enrichments in Apollo lunar highlands soils, probably by early volcanism (KRÄHENBÜHL *et al.*, 1973a). Highly mobile Tl was also thermally volatilized and re-

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distributed—*i.e.* mobilized—in lunar anorthosites but not in basalts, norites or rhyolites (KRÄHENBÜHL *et al.*, 1973a, b): ALHA81005 also shows this (VERKOUTEREN *et al.*, 1983).

If ALHA81005 had experienced substantial shock heating during its impact launch earthward at  $\geq 2.4$  km/s, the most mobile elements (Ag, Zn, Tl, Cd) at least should exhibit preferential loss relative to other volatile/mobile ones. This, for example, is shown by heavily shock-loaded L chondrites (HUSTON and LIPSCHUTZ (1984) and papers cited therein). In fact, even the most mobile elements indicate at least 1.3% Cl-equivalent admixed material, *i.e.* levels exhibited by less mobile ones (VERKOUTEREN *et al.*, 1983) so that loss from ALHA81005 is not detectable.

Other samples (Yamato(Y)-791197, -82192 and -82193), found 400 km from the Allan Hills, also seem of lunar origin. The first of these, an anorthositic breccia, resembles ALHA81005 (YANAI and KOJIMA, 1984): the others (which may well be paired) exhibit physically distinctive features (YANAI and KOJIMA, 1985b). Early information reported Y-791197 as “an anorthositic regolith breccia,... remarkably similar to lunar highland regolith breccias” (YANAI and KOJIMA, 1984). A Consortium was established, in which we were privileged to participate, to study Y-791197, in part to compare it with ALHA81005 and examine whether they are pieces of the same fall or derive from the same impact on the moon. For this, we determined our usual suite of trace elements and we report the results here.

## 2. Experimental

We received our sample (,88) as 2 chips, weighing 71 and 19 mg that we denoted as a and b, respectively, and analyzed separately. Our samples, those of LINDSTROM *et al.* (1986), OSTERTAG *et al.* (1985) and WARREN and KALLEMEYN (1986) derive from the same 1.9 g parent (,61): we do not know whether ,61 was also the source of the sample analyzed by FUKUOKA *et al.* (1985). The significance of this will emerge later.

We sealed each sample (without further cleaning or processing) in separate, evacuated synthetic quartz (Suprasil) vials for a 5-day irradiation at a nominal thermal neutron flux of  $10^{14}$  cm<sup>-2</sup>s<sup>-1</sup> in the University of Missouri Research Reactor. Monitors, prepared as described by VERKOUTEREN *et al.* (1983), were divided into four sets to facilitate chemical separation and radiochemical purification: a (Bi, Tl); b (Co, Ga, In, Se); c (Ag, Cd, Rb, Te, U); d (Au, Cs, Sb, Zn).

Monitor and sample processing, counting and data reduction were as described by VERKOUTEREN *et al.* (1983) except that initial chemical separation steps were abbreviated in the following way. After dissolving the Na<sub>2</sub>O<sub>2</sub>-NaOH fusion cake in dilute HCl, we evaporated the solution to dryness and took the solid up in 0.55 N HCl. Insoluble material was saved for Ag processing and we loaded the supernate onto an AG 1×8 anion exchange column. The eluant, containing Co, Cs, Ga, In, Rb, Sb, Se and Te, was adjusted to 3 N HCl and saturated with SO<sub>2</sub> to precipitate Se and, after brief boiling, Te. We adjusted the pH of the supernate to 8, precipitating Co, Ga, In and Sb hydroxides and leaving Cs<sup>+</sup> and Rb<sup>+</sup> in solution. We separated Ga and In by solvent extraction. After evaporating the Co, Sb fraction to dryness, we took the residue up in 0.75 N HCl and precipitated Sb<sub>2</sub>S<sub>3</sub> with H<sub>2</sub>S. Further separations and

purifications were as described by VERKOUTEREN *et al.* (1983). Chemical yields exceeded 50% for all monitors and nearly all samples (except for Ga and Sb (6–12%) and Ag (20%) in ,88a and ,88b and Te (42%) in ,88a). Radiochemical purity was quite satisfactory in all cases.

### 3. Results

By any standard, duplicate analyses of Y-791197,88 disagree markedly (Table 1), often by an order of magnitude or more. To visualize this, we depict Y-791197 data of Table 1 in Fig. 1, together with ALHA81005,10 means and ranges for the duplicates (VERKOUTEREN *et al.*, 1983), where these exceed the symbol size. [Taking ALHA81005 results (VERKOUTEREN *et al.*, 1983) as indicative of expected precision for duplicate analyses, relative standard deviations of the mean are 2–7% for 9 elements (Au, Bi, Co, Cs, Ga, Se, Tl, U, Zn), 13% for In and Sb and about 20% for Ag, As and Te.] To facilitate comparison, all data in Fig. 1 are normalized to Cl concentrations (ANDERS and EBIHARA, 1982).

Table 1. Trace element contents of Y-791197 compared with those in ALHA81005 and Apollo sample 66095.

Element*	Y-791197,88			Y-791197**	Apollo 66095		
	a	b	Geom. mean	ALHA81005	Range (No. of analyses)	Ref.***	Geom. mean
Siderophile							
Co (ppm)	18.2	21.2	19.6	0.89	44.0 (1)	b	44
Au	18.6	30.7	24	7.5	17.9 (1)	a	18
Sb	1.4	17.2	4.9	3.0	6.9 (1)	a	6.9
Ga (ppm)	3.16	37.4	11	4.2	3.8 (1)	b	3.8
Mobile							
Se	193	457	300	1.2	314 (1)	a	310
Te	21.3	228	70	7.1	68–80 (2)	a, f	74
Bi	3.5	45	12	17	1.62–12 (2)	a, c	4.4
In	13	8.4	10	7.9	680 (1)	b	680
Ag	6.1	43.9	16	5.9	2.0 (1)	a	2.0
Zn (ppm)	18.0	189	58	12	8.65–92.0 (4)	a, b, c, e	27
Tl	12	3.5	6.4	4.4	112–197 (2)	a, c	150
Cd	170	220	190	9.5	288 (1)	a	290
Lithophile							
Rb (ppm)	0.68	2.66	1.3	3.2	1.1–11 (5)	a, b, d, f	3.1
Cs	36.8	216	89	4.0	55–400 (2)	a, b	150
U	153	378	240	1.8	138–1100 (6)	a, b, d, f	600

\* Units are ppb unless otherwise noted.

\*\* Allan Hills A81005 data from VERKOUTEREN *et al.* (1983).

\*\*\* Reference: (a) KRÄHENBÜHL *et al.* (1973a); (b) BRUNFELT *et al.* (1973); (c) ALLEN *et al.* (1974); (d) HUBBARD *et al.* (1973); (e) DUNCAN *et al.* (1973); (f) JOVANOVIĆ and REED (1973).

Few of the elements we determine are measured by others (Table 2). Except for Co, which is almost uniquely homogeneous and for which our and other data agree well (Table 2), all other results indicate Y-791197 to be unusually heterogeneous. One of two Au data of FUKUOKA *et al.* (1985) agrees well with our value for ,88b: all other

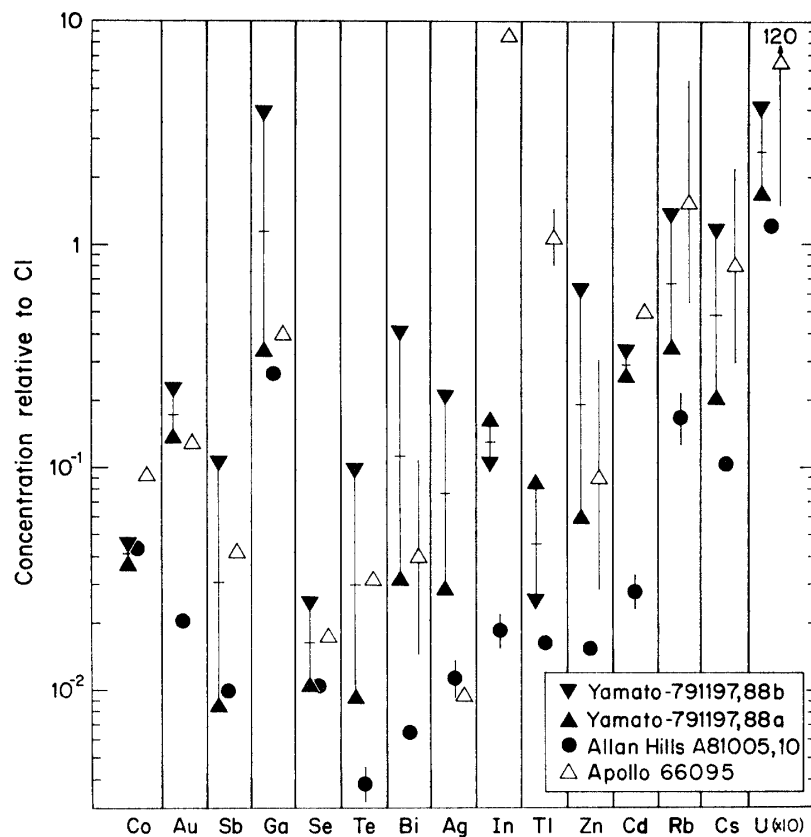


Fig. 1. Trace element concentrations in two aliquots of Y-791197,88 and ALHA81005,10 and Apollo 66095 ("Rusty Rock"). Geometric means for Y-791197 are indicated by horizontal lines. Points for ALHA81005 are mean values of duplicate runs; ranges are indicated where they exceed the point size. For Apollo 66095, vertical lines indicate ranges when replicates were analyzed. To facilitate discussion, all data are normalized to Cl concentrations. Generally, concentration levels in Y-791197 are higher than those in ALHA81005 and comparable to those in Apollo 66095, a sample suggested as containing condensed lunar volcanic emanations.

Table 2. Comparison of whole rock analyses of Y-791197.

	Co (ppm)	Au (ppb)	Ga (ppm)	Zn (ppm)	U (ppb)
This work ,88a	18.2	18.6	3.16	18.0	153
,88b	21.2	30.7	37.4	189	378
geom. mean	19.6	24	11	58	240
FUKUOKA <i>et al.</i> (1985)	19.8	2.5 36.5			
LINDSTROM <i>et al.</i> (1986)	19.4	3.4			120
OSTERTAG <i>et al.</i> (1985)	17.0	2.1	9.8	65	129
WARREN and KALLEMEYN (1986)	18.4		3.2	22	

results are considerably lower even than our datum for ,88a (Table 2). Most other results, *i.e.* U data and Ga and Zn values by WARREN and KALLEMEYN (1986), agree with contents in ,88a (Table 2). The sample analyzed by OSTERTAG *et al.* (1985) contains Ga and Zn in amounts intermediate between those of ,88a and b (Table 2), indeed very similar to geometric means for ,88 (Table 1).

#### 4. Discussion

The broad compositional variability of Y-791197 argues that trace elements are very heterogeneously distributed, particularly since most, if not all, aliquots studied by us and others came from the same 1.9 g portion of it. Every element but Co is significantly enriched in Y-791197,88b relative to ALHA81005: most are also enriched in ,88a (Fig. 1). Geometric means for Y-791197,88 indicate enrichments of as much as  $17\times$ , averaging  $6\times$ , relative to ALHA81005 (Table 1).

Lithophilic trace elements, Au, and especially, volatile/mobile elements demonstrate that Y-791197 and ALHA81005 do not derive from the same rock: other chemical and physical investigators accord with this view (LINDSTROM *et al.*, 1986; NISHIZUMI and ELMORE, 1985; OSTERTAG *et al.*, 1985; SUTTON, 1985; WARREN and KALLEMEYN, 1986). This view may not be unanimous, partly because of the compositional heterogeneity of Y-791197 and partly because few highly volatile/mobile elements—which are most clearly different—are determined by other analysts. OSTERTAG *et al.* (1985) specifically noted that their most discrepant elements in Y-791197 and ALHA81005 were Ga and Zn, the most volatile of the ones they analyzed. Other elements listed in Table 2 are not very volatile. Clearly, a low temperature thermal history difference distinguishes Y-791197 from ALHA81005.

Since all in the Y-791197 Consortium conclude that this meteorite derives from the lunar highlands (see other papers in this volume) we see no reason to belabor that point. Highlands samples as volatile-rich as Y-791197 are rare but do exist. Perhaps the closest match exists with 66095 (“Rusty Rock”), an anorthositic gabbro, data for which are summarized in Table 1 and depicted in Fig. 1. Contents of most elements accord with those in Y-791197, highly volatile/mobile In and Tl being the most clearly discrepant. Curiously, these are the only elements whose contents in ,88a exceed those in ,88b. Since high trace element enrichments in 66095 seem due to lunar volcanic (perhaps fumarolic) material condensed after its formation (KRÄHENBÜHL *et al.*, 1973a and references cited therein), a similar cause for enrichments in Y-791197 seems reasonable. The fortuitous inclusion of a large volatile-rich inclusion in ,88a or b is precluded by the unique Cl-normalized variations in each sample (Fig. 1). Hence, assuming lunar volcanic condensate to be responsible for high volatile/mobile and lithophile enrichments in Y-791197, its enormous compositional heterogeneity (on the cg scale) suggests trace element introduction prior to regolith compaction into breccia. This is supported, for what it is worth, by differences in Tl/Cs and Tl/U ratios in Y-791197 from the well-defined ratios of  $1.0 \times 10^{-2}$  and  $2.8 \times 10^{-3}$ , respectively, found for lunar samples unaffected by volcanism (KRÄHENBÜHL *et al.*, 1973b; VERKOUTEREN *et al.*, 1983).

Since enrichments in Y-791197,88 are more variable than those in ALHA81005 (VERKOUTEREN *et al.*, 1983), it is very difficult to establish if trace element mobilization occurred during its lunar launch, *i.e.* whether Y-791197 on the moon contained even greater amounts of the most mobile elements, some proportion of which were lost by heating as the meteorite escaped earthward. Since In and Tl contents in Y-791197 are not as high as those in 66095, this could indicate initially even larger amounts in Y-791197: however, Tl, at least, is well known to be irregularly distributed in lunar anortho-

sites because of its high mobility (KRÄHENBÜHL *et al.*, 1973a, b). Moreover, the Zn and Cd contents of Y-791197 are not markedly low relative to those in 66095. OSTERTAG *et al.* (1985) concluded that shock-loading in Y-791197 did not exceed 25 GPa: mobile element loss is detectable in L chondrites shock-loaded at 20–35 GPa (WALSH and LIPSCHUTZ, 1982).

Compositional and cosmogenic differences between ALHA81005 and Y-791197 are so strong that the two specimens could not derive from the same meter-sized rock. However, existing data are insufficient to establish whether Y-791197 and ALHA81005 were excavated from the moon in a single impact. The samples were found 4000 km apart but, even if they were ejected simultaneously, the lunar meteorites need not constitute part of a normal strewn field. They could have had somewhat different orbital elements or, even with the essentially the same one, could have been captured on different orbits of the earth. On the moon, Y-791197 and ALHA81005 were separated by a vertical distance on the dm scale (NISHIZUMI and ELMORE, 1985; SUTTON, 1985; TAKAOKA, 1986) but there is no means of determining horizontal separation. From volatile/mobile trace elements, as described, Y-791197 and ALHA81005 differ markedly but samples from the Apollo 16 site differ as much. A large enough impact, excavating a km<sup>2</sup>-sized area there, could have yielded samples as different as are these two Antarctic lunar anorthosites. Petrographically, Y-791197 and ALHA81005, are similar and exhibit similar sorts of unusual components, arguing that they derive from the same lunar region (LINDSTROM *et al.*, 1986; TAKEDA *et al.*, 1986). But, there is no means of determining the extent of this region or, with certainty, its general location. Orbital X- and  $\gamma$ -ray measurements indicate a lunar farside composition consistent with the low KREEP content of the two Antarctic anorthosites, prompting the suggestion that they derive from the farside (LINDSTROM *et al.*, 1986; OSTERTAG *et al.*, 1985; WARREN and KALLEMEYN, 1986). However, VLT mare basalts are present in the samples and, as pointed out at this Symposium, maria are rare on the farside and mare basalts should also be rare in breccias from there. MCFADDEN *et al.* (1986) suggests another possible source (the crater Eimmart A on the eastern lunar limb near M. Crisium) which, from reflectance spectroscopy, has a mineralogy appropriate to Y-791197.

## 5. Conclusions

Y-791197, clearly of lunar highlands origin, contains very variable and, at times, large amounts of siderophile and mobile trace elements. In these respects (and, from work by others, in cosmogenic effects) it differs markedly from ALHA81005, indicating that the two Antarctic lunar highlands breccias were not part of the same rock. In its volatile/mobile trace element contents, Y-791197 most closely resembles Apollo 16 "Rusty Rock" (66095), an anorthositic gabbro enriched by volcanic (even fumarolic) lunar exhalations. Extensive data by others demonstrate that Y-791197 and ALHA81005 derive from the same general lunar region, which was not sampled by the Apollo or Luna programs. However, a choice of a single *vs.* multiple impact(s) for Antarctic lunar meteorite ejection is not possible at this time. It could be that results from study of Y-82192 and/or 82193 may help decide this question.

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